Specification

AN EFFICIENT METHOD FOR MULTI-PATH RESISTANT CARRIER AND TIMING FREQUENCY OFFSET DETECTION

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Reference to Prior Application

This application claims the benefit of a previously filed U.S. Provisional Patent Application No. 60/455,152 filed on March 14, 2003, and entitled "AN EFFICIENT METHOD FOR MULTI-PATH RESISTANT CARRIER AND TIMING FREQUENCY

10   OFFSET DETECTION."

BACKGROUND OF THE INVENTION

Field of the Invention

15   The present invention relates generally to the field of wireless receivers and particularly to a method and apparatus for detecting carrier frequency and timing offsets to enhance the receiver performance under the effects of multi-path channel.

Description of the Prior Art

20   As computers have gained enormous popularity in recent decades, so have networking the same allowing for access of files by one computer from another. More recently and with the advent of wireless communication, remote and wireless networking of computers is gaining more and more notoriety among personal users, small and large business owners, factory facilities and the like.

With regard to the wireless networking of personal computers including laptops, a particular modem, namely modems adapted to the IEEE 802.11a or 802.11g industry standard, are commonly employed. That is, an antenna is placed inside or nearby the personal computer and an RF chip receives signal or data through the antenna and an

5   analog-to-digital converter, typically located within the personal computer (PC), converts the received signal to baseband range. Thereafter, a baseband processor is employed to process and decode the received signal to the point of extracting raw data, which may be files transferred remotely and wireless, from another PC or similar equipment with the use of a transmitter within the transmitting PC.

10   There are several prior art apparatus and techniques for implementing 802.11a/g modem receivers, however, such prior art have not successfully utilized the fullest potential of the 802.11a/g modem. For example, the maximum rate of this type of modem device is 54 Mbits/sec. but in the presence of multi-path channel, use of current prior art methods and apparatus does not allow for reception of data at such rates. In fact,

15   successful reception of data under multi-path channel conditions currently takes place at lower rates or may fail altogether.

Furthermore, in areas other than open locations, such as smaller office cubicles located within the inter structure of a building, prior art receivers are known to only operate at rates lower than that of the maximum operational rate of the modem, such as

20   54 Mbits/sec., thus preventing a user from receiving files from another PC at optimal rates. This is generally due to the prior art techniques' limitations in operating within multi-path channel conditions, which occur mostly in closed areas, such as those mentioned hereinabove. In particular, multi-path channel may degrade a receiver's ability

to acquire and track carrier frequency and timing rate offsets. For 802.11a/g modems that

modulate data using orthogonal frequency division multiplexing (OFDM), multi-path

channel may lead to dramatic loss in data detection performance because such frequency

offsets may result in constellation distortion (e.g. unwanted rotations) and destroy

5   orthogonality between the carriers causing inter-carrier interference (ICI). Thus, for high

performance 802.11 a/g modems require precise carrier and timing offset controls.

In light of the foregoing, it is desirable to develop an OFDM modem that can

receive signals, such as those specified by the 802.11 a/g standards, accurately in the

presence of multi-path channel and with the ability to achieve maximum data rate

10   throughputs. The presence of multi-path channel should be mitigated in such a way as to

reduce the effect of noise, constellation distortions and ICI caused by poor carrier and

timing offset controls. Furthermore, it is essential that enhancing the performance of the

OFDM receiver be accomplished without adding considerable complexity to the

hardware resources employed in processing the received OFDM signal.

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SUMMARY OF THE INVENTION

Briefly, an embodiment of the present invention includes a modem receiver for

receiving signals having a frequency domain equalizer training module (FTM) being

responsive to a frequency channel response for processing the same to generate one or

20   more frequency domain equalizer (FEQ) coefficients, said modem receiver being

responsive to an input signal for processing the same to generate said frequency channel

response, said input signal being generated from transmission of a transmitted signal, said

frequency channel response for including one or more pilot tones, said FEQ coefficients

for including one or more pilot tone FEQ coefficients. The modem receiver further includes an offset weight determination (OWD) module being responsive to said pilot tone FEQ coefficients for processing the same to generate one or more carrier weights, said modem receiver for using said carrier weights to generate a carrier offset, said OWD module for using said pilot tone FEQ coefficients to generate one or more timing weights, said modem receiver for using said timing weights to generate a timing offset, said modem receiver for reducing the effects of faded pilot tones on determination of said timing offset and said carrier offset between said transmitted signal and said input signal.

The foregoing and other objects, features and advantages of the present invention will be apparent from the following detailed description of the preferred embodiments which make reference to several figures of the drawing.

IN THE DRAWINGS

Fig. 1 shows a block diagram 10 of the architecture of an IEEE 802.11g or 802.11a orthogonal frequency division multiplexing (OFDM) modem receiver, in accordance with an embodiment of the present invention.

Fig. 2 shows a profile of frequency domain equalizer (FEQ) magnitudes for a channel with mild fading, in accordance with an embodiment of the present invention.

Fig. 3 shows a profile of FEQ magnitudes for a channel with severe fading, in accordance with an embodiment of the present invention.

Fig. 4 shows a block diagram outlining the interaction between an FEQ and a frequency offset detection module, in accordance with an embodiment of the present invention.

Fig. 5 illustrates a block diagram outlining the interaction between an FEQ and a timing offset detection module, in accordance with an embodiment of the present invention.

Fig. 6 illustrates a block diagram outlining computation of the timing and carrier

5   weights, in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to Fig. 1, a block diagram 10 of the architecture of an IEEE

10   802.11a or 802.11g (802.11 a/g) orthogonal frequency division multiplexing (OFDM)

modem receiver is shown, in accordance with an embodiment of the present invention.

The block diagram 10 includes a first frequency shifter 12, a buffer/interpolator 14, a low

pass filter 16, a second frequency shifter 18, a serial to parallel (S/P) converter 22, a fast

Fourier transform (FFT) analyzer 24, a frequency domain equalizer (FEQ) 26, a decoding

15   module 28, a frequency offset detection module 30, a frequency loop filter or a carrier

loop filter 32, a timing loop filter 38, a timing numerically controlled oscillator (NCO)

40, a carrier NCO 34, a timing offset detection module 36 and a feedforward correction

module 42.

Input signals comprising information packets are received by the frequency shifter

20   12, which is coupled to the buffer/interpolator 14. The buffer/interpolator 14 is coupled

to the low pass filter 16 that is coupled to the frequency shifter 18. The latter is coupled

to the prefix strip 20. The prefix strip 20 is coupled to the FFT analyzer 24, which is

coupled to the FEQ 26. The FEQ 26 is coupled to the feedforward correction module 42,

the timing offset detection module 36, and the frequency offset detection module 30. The

frequency offset detection module 30 is coupled to the frequency loop filter 32, which is coupled to the NCO 34. The latter is coupled to the frequency shifter 18. The timing offset detection module 36 is coupled to the timing loop filter 38, which is coupled to the NCO 40. The NCO 40 is coupled to the buffer interpolator 14. The feedforward correction module 42 is coupled to the decoding module 28.

Input signals in the intermediate frequency (IF) range, such as 10 Mega Hertz (MHz), are received by the frequency shifter 12. The transmitted signal is initially received in an analog format by an antenna through a radio frequency (RF) receiver (not shown in Fig. 1). The received signal is converted by an analog-to-digital converter (ADC) into digital format to generate the input signals. In an alternative embodiment of the present invention the RF receiver produces a base band signal directly (Zero-IF) thereby eliminating the need for the frequency shifter 12.

However, communication channel conditions are often such that multiple copies of the transmitted signal are received by the RF receiver because of multiple reflections of the transmitted signal from objects and surfaces (e.g. walls, ceiling, trees) in the receiver environment. Such a mode of reception is referred to as a multi-path channel. Multi-path channel may impede detection and compensation of the timing offset and carrier frequency or carrier offset between the transmitted signal and the input signal. The present invention alleviates such negative multi-path effects by correcting carrier frequency and sampling rate offsets through the frequency offset detection module 30 and the timing offset detection module 36, as described in more detail hereinbelow.

In one particular baseband RF implementation, the input signal at the intermediate frequency (IF) is converted by the frequency shifter 12 to a baseband (frequency) signal,

which is transferred through the buffer/interpolator 14 where the timing offset is corrected to generate a buffer/interpolator output. The buffer/interpolator output is transferred through a lowpass filter, in order to remove unused spectrum, to the frequency shifter 18. The frequency shifter 18 applies the correction for the carrier

5   frequency offset or carrier offset to the filtered baseband signal based on the frequency feedback information in the form of frequency correction signal received from the NCO 34 to generate the adjusted signal. The adjusted signal is transferred to the prefix strip 20, where the guard interval between symbols is removed. The output of the prefix strip 20 is transferred to the serial-to-parallel converter S/P 22 where a vector signal of 64

10   sample values is generated. The vector signal of 64 samples is then transferred to the FFT module 24.

In one embodiment of the present invention, the FFT module 24 performs a 64-point FFT converting the 64 time domain samples into 64 frequency domain subcarriers, which comprise one data symbol. As specified by the 802.11a/g standard, each symbol

15   has 64 subcarriers, of which 12 are reserved for guard band separation and 52 are dedicated to the transmitted signal. Of these 52 subcarriers dedicated to the transmitted signal, 4 are allocated as pilot tones for timing and frequency correction while the remaining 48 subcarriers carry the contents of the information packet (i.e., data subcarriers).

20   To correct the effects of multi-path channel the FEQ 26 applies complex scaling factors, or gains and phases, to compensate for the channel response for each data symbol. The FEQ 26 is trained once during the preamble portion of the information packet, by an FEQ Training Module (FTM) (discussed in detail in relation to Fig. 6) and

as discussed in detail in a Provisional Patent Application with serial no. 60/455,157, entitled "EFFICIENT SUBCARRIER WEIGHTING TO ENHANCE RECEIVER PERFORMANCE", filed on March 14th, 2003, the inventors of which are Alain Chiodini and Thomas Pare, and the disclosure of which is herein incorporated by reference in its entirety. The FEQ 26 is trained to correct for the instantaneous channel conditions on each subcarrier for the remainder of the information packet. Specifically, if a particular subcarrier is deeply faded, the FEQ 26 applies a large gain thereto to amplify the response of the subcarrier.

Large FEQ gain, however, also amplifies the noise component associated with the subcarrier and, if the particular subcarrier is a pilot tone, the large FEQ may adversely affect the performance and stability of the carrier frequency and timing frequency offset loops. To avoid adverse multi-path channel, the frequency offset detection module 30 and the timing offset detection module 36 apply appropriate weights to the pilot tones. The weights are computed during the preamble portion using the FEQ coefficients corresponding to the pilot tones, or the pilot tone FEQ coefficients, by the Offset Weight Determination (OWD) module, as discussed hereinbelow. The carrier weights: W_1, W_2, W_3 and W_4 are transferred to the frequency offset detection module 30, while the timing weights, M_1 and M_2, are sent to the timing offset detection module 36. The weights are used throughout the duration of the packet to ensure proper functioning of the carrier and timing offset loops by mitigating the high pilot noise that can result from the presence of a multi-path channel, as discussed above.

The timing and carrier offset loops are updated on a per symbol basis, using the four pilot tones from the FEQ module 26 to update the frequency offset detection module

30 and the timing offset detection module 36, as depicted in Fig.1. The output from the frequency offset detection module 30 updates the loop filter 32, which causes the NCO 34 to produce proper frequency correction that is applied at the multiplier shifter 18, on a sample-by-sample basis. In another embodiment of the present invention, NCO 34

5   generates proper frequency correction that is applied at the multiplier shifter 18 on a symbol-by-symbol basis. Similarly, the timing detection module 36 output updates the timing loop filter 38 which generates a timing loop filter output used in the timing NCO 40 to control the rate of interpolation at the buffer/interpolator 14 by generating a timing adjustment signal. The buffer/interpolator 14 resamples the baseband signal to adjust the

10   timing offset using the timing adjustment signal. In total, the blocks mentioned hereinabove together with the common blocks 16, 20, 22, 24 and 42 comprise the frequency offset and timing offset control loops.

According to the 802.11a/g standard, among the 52 subcarriers 4 are the pilot tones 50-56, as shown in Fig.2. The pilot tones are essentially equally spaced among the

15   subcarriers, and using the numbering scheme shown in Fig. 2, correspond approximately to the 7, 21, 35, and 49th subcarriers. For each symbol as processed by the FEQ 26, the four pilot tones are extracted and used to compute the carrier offset. Each pilot tone is demodulated by the FFT 24, FEQ 26 processing as a BPSK (binary phase shift keying) symbol, and may be expressed as a complex number, p_i, i = 1, 2, 3, 4, corresponding to

20   the locations 7, 21, 35 and 49, respectively, as shown in Figs. 2 and 3.

The effect of carrier offset on the pilots is to introduce a phase, or rotation, on each of the pilot symbols equally. The offset detector needs to accurately measure this

rotation so that it can serve as a feedback signal for the frequency offset control loop. For example, if the four pilot tones in a noise free case were perfect BPSK symbols:

$p_i = 1 + 0j$, for $i = 1, 2, 3, 4$, then the same pilot tones experiencing rotation caused by the carrier offset would be $p_i = e^{j\phi}$, for $i = 1, 2, 3, 4$, where ϕ is the angle of rotation or phase.

5   Note that the carrier offset affects each carrier with the same phase ϕ, hence being referred to as common phase error (CPE). In a prior art implementation a carrier offset detector measures CPE in an 802.11a/g modem by simply summing the pilot tones and computing the angle of the result as

$$CPE = angle(\Sigma p_i) = atan(imag(\Sigma p_i)/real(\Sigma p_i)). \quad (1)$$

10   In equation (1), the angle is computed using an arctangent function, *atan()*, and *real()* and *imag()* functions representing real and imaginary parts of the argument in parantheses, respectively. The CPE angle is the feedback signal for the carrier offset loop, and is sent as the input signal to the loop filter 32 shown in Fig. 1. The problem with the prior art implementations arises when one or more of the pilot tones becomes corrupted due to

15   multipath channel fading.

Referring now to Fig. 2, a profile of FEQ magnitudes is shown that is consistent with a channel experiencing mild fading due to multipath channel. Shown in Fig. 2 are the 52 subcarriers, numbered along the horizontal axis whose FEQ magnitudes are indicated with small circles on the vertical axis measured in decibels (dB). As shown in

20   Fig. 2, the relative difference between the highest FEQ magnitude and the lowest FEQ magnitude is approximately 3 dB, indicating that the channel response is not faded severely enough to require application of a large gain. Hence, the profile of the FEQ magnitudes shown in Fig. 2 that would be computed during the packet preamble is that of

a channel with mild fading. In particular, the FEQ magnitudes 50-56 are all within approximately 2 dB gain of each other, and thus the corresponding pilot tones provide a reasonably good measure of the CPE.

On the other hand, referring now to Fig. 3, a profile of FEQ magnitudes for a channel with a severe fading is shown that might be representative of a channel condition present in a typical office environment (cubical walls, ceilings, etc.). Note that the FEQ values corresponding to the pilot tones or the pilot tone FEQ coefficients 60-66 do not have values close in magnitude as for the previous condition depicted in Fig. 2. In particular, the pilot tone 66, located at the 49th subcarrier, is severely faded, as indicated by the high gain of more than 14 dB, compared to the other pilot tones 60-64 which only require FEQ gains of approximately 2 dB. Thus, the pilot tone 66 is considered severely faded, and as such provides a poor quality estimate of the CPE. Indeed, the large FEQ gain on the pilot tone 66 will lead to a high noise component in the calculation of the CPE as described by equation (1) above. This may have an adverse effect on the operation of the frequency offset control loop and simulations indicate that for various hardware implementations the particular channel condition shown in Fig. 3 will cause frequency offset control loop instability and loss of the received packet. In contrast, mild fading of the channel shown in Fig. 2 may have no noticeable effect on the stability of the frequency offset loop. The present invention overcomes such sensitivity to channel conditions by augmenting determination of the CPE with a set of weights based on the channel fade condition.

Specifically, a set of weights W is determined by the offset weight determination module OWD during the preamble portion of the information packet using the magnitude

portion of the FEQ coefficients corresponding to the pilot tones. The carrier weights, W_1-W_4 are proportional to the inverse of the squared FEQ magnitudes, and are evaluated as

$$W_i = round(-log(|FEQ_i|^2)). \quad (2)$$

5   In equation (2), $|FEQ_i|^2$ is the magnitude squared of the ith pilot tone FEQ coefficient, where $i = 1$ through 4. The round function in equation (2) rounds off the log value in parentheses to the nearest integer rendering W_i an integer value. Log in equation (2) represents the logarithmic function to base 2. For example, using equation (2) the set of carrier weights W for the pilot tones 50-56 is determined to be W = [2, 4, 2, 1].

10   Similarly, equation (2) using the FEQ coefficients shown in Fig. 3 yields the set of weights W = [2, 3, 1, 8]. It is evident from the second set of weights that a relatively large weight $W_4 = 8$, is assigned to the 4th pilot tone 66. The carrier offset weights are used to augment the basic CPE equation (1) to form a modified CPE^W as:

$$CPE^W = angle(\Sigma\, shr(p_i, W_i) = atan(imag(\Sigma\, shr(p_i, W_i))/real(\Sigma shr(p_i, W_i))). \quad (3)$$

15   In equation (3) $shr(p_i, W_i)$ is a binary shift right function which shifts the integer value of p_i to the right by W_i places. Consequently, using (3), the pilot tone 66 (i.e. p_4) is shifted right 8 places, i.e., it is divided by $2^8 = 256$, which effectively nullifies the effect of the pilot tone 66 on the CPE^W calculation. The result of such division is a set of weighted pilot tones. Accordingly, any large noise component associated with the pilot

20   66 has minimal impact on the operation of the frequency offset control loop. For the channel condition depicted in Fig. 2, the set W = [2, 4, 2, 1] indicates less severe channel condition with the deepest pilot tone fading resulting in a weight of $W_2 = 4$, corresponding to the pilot tone 52. The corresponding pilot tone p_2 will be divided by 2^4

= 16 to generate a weighted pilot tone, thereby allowing more information to be used than in the case of the severely faded pilot tone 66 in Fig. 3. In the case of clear, or flat channels, the set of weights is simply all unity, W = [1, 1, 1, 1], meaning that all the pilot tones will be weighted equally which will provide the best noise attenuation and give the

5   best estimate of the common phase error CPE^W, given by (3).

Referring now to Fig. 4, a block diagram depicting the hardware implementation of the CPE^W computation detailed in equation (3) is shown, in accordance with an embodiment of the present invention. Fig. 4 depicts an FEQ module 70 coupled to a carrier offset detection or CPE^W module 71. The FEQ module 70 is used to gain and

10   phase adjust the pilot symbols, which are then passed to the CPE^W module 71. The process depicted in Fig. 4 occurs once for each data symbol in the information packet. In the CPE^W module 71 there is a simple polarity adjustment 72 performed according to the IEEE standard 802.11a-1999, page 23, to generate phase-corrected pilot tones. The phase-corrected pilot tones are scaled by the bank of carrier weights W_1-W_4 (74-80), that

15   are derived according to equation (2) during the preamble portion of the information packet by the OWD module to generate weighted pilot tones, as discussed hereinbelow. The weighted pilot tones are then summed together by the adders 82-86, and the result is input to the Coordinate Rotation Digital Computer CORDIC module 88, which includes an efficient hardware implementation of the *atan()* function. Note that the operation

20   performed by the blocks included in the CPE^W module 71 in Fig. 4 is a direct implementation of CPE^W equation (3), as discussed above. The angle output of the CORDIC module 88 is then passed to the frequency loop filter 90. The frequency loop filter output, generated by filter 90, is processed by the NCO 34 to generate a real-time

frequency correction signal that is applied to the baseband signal, as shown at the frequency shifter 18 in Fig. 1.

To summarize, the CPE^W module 71 shown in Fig. 4 is a module that computes an estimate of the instantaneous carrier offset represented by the CPE^W during the steady state operation of the carrier control loop, shown in Fig. 1. That is, the carrier offset is determined by computing the CPE^W. The CPE^W module 71 automatically prevents the effects of multi-path channel fading from corrupting the CPE calculation by applying a set of carrier weights to the pilot symbols that are included with each data symbol in the packet. The weights are computed once at the beginning of the packet during the preamble, and immediately after the computation of the FEQ. The FEQ coefficients corresponding to the pilot tones provide the channel fade information necessary to compute the set of weights, as specified by equation (2). The weights W1-W4 computed during the preamble are then transferred to the CPE^W module 71 to be used for steady state operation during the data portion of the information packet.

An important aspect of the CPE^W module 71 module is that the effective gain of the module remains relatively the same under varying channel conditions. That is to say, given a fixed CPE value (in degrees), and two very different channel conditions, as say depicted in Figs. 2 and 3, even though the set of weights employed by the module may vary the CPE angle computed will be the same in a noise free channel. Relative constancy of the effective gain is critical in order for closed loop stability to be maintained under varying channel conditions. If the effective gain were to vary freely as the weights W_1-W_4 changed, then the loop gain would vary. Variation of the loop gain could cause loss in either gain and/or phase margins and possibly cause the loop to

become unstable, leading to packet reception failure. An important feature of the CPE^W module 71 is that the weightings are applied to the complex pilot symbols before the CORDIC module 88. The CORDIC module 88 naturally converts the weighted sum back into dimensionless angular coordinates, thus maintaining the gain of the CPE^W module

5   71. In this sense, the CPE^W module 71 mitigates the noise effects of the fading channel while maintaining loop stability conditions that are robust to varying channel conditions.

In addition to the feedback control, the CPE^W also provides the signal to the feedforward correction module 42. In the feedforward correction module 42 the CPEW corrects a well-known error caused by the imperfections in the analog radio frequency

10   (RF) circuit, as discussed in detail in Garcia Armada, Ana and Calvo, Miguel, "Phase Noise and Sub-Carrier Spacing Effects on the Performance of an OFDM Communication System", IEEE Communications Letters, Vol. 2, No. 1, January 1998.

Noise in the voltage controlled oscillator (VCO) circuits is known to cause spurious rotations in the equalized data symbol, X, generated by the FEQ module 26.

15   The FEQ OFDM equalized data symbol is comprised of 48 subcarriers:

$$X = [x_1, x_2, ...,x_{48}]$$

Each subcarrier is a complex symbol, either BPSK, quadrature phase shift keying (QPSK), 16 quadrature amplitude modulation (QAM), or 64QAM. These subcarrier equalized data symbols are corrected by forming the phase correction $P_{correction}$ based on

20   the CPE^W as:

$$P_{correction} = e^{-jCPEW}.$$

The feedforward correction module 42 computes $P_{correction}$ and applies the correction to the OFDM equalized data symbol by multiplying each subcarrier with $P_{correction}$ to generate a corrected equalized data symbol $X_{corrected}$ as:

$$X_{corrected} = P_{correction} * X = [e^{-jCPEW} * x_1, e^{-jCPEW} * x_2, \ldots, e^{-jCPEW} * x_{48}].$$

5   Computing the feedforward correction as indicated hereinabove with CPE^W, rather than using CPW, provides protection for the equalized data symbol against excess RF carrier impairment due to multi-path fading, in a beneficial way analogous to the feedback implementation discussed hereinabove for the carrier loop filter.

Referring now to Fig. 5, a block diagram outlining the interaction between an

10   FEQ module 100 and a timing offset detection module 102 is shown, in accordance with an embodiment of the present invention. The FEQ module 100 is coupled to the timing offset detection module 102 by the same interface as that depicted in Fig. 4, which depicts the carrier or frequency offset detection module 71. The timing offset detection module 102 includes the polarity adjustment module 104 coupled to 2 summation

15   junctions 106 and 108, which are coupled to 2 CORDIC modules 110 and 112, respectively. The CORDIC modules 110 and 112 are coupled to 2 weighting modules 114 and 116, respectively, and the latter are coupled to a normalization module 120. The normalization module 120 is coupled to the timing loop filter 122.

The FEQ module 100, during the packet decoding process, transfers the pilot

20   tones p_i, where i ranges from 1 through 4, to the polarity adjust module 104, as discussed aboveinabove and as specified in the IEEE Standard 802.11a-1999, page 23. To determine the timing offset, p_2 and the conjugate of p_3 are added at the summation junction 106, and p_1 and the conjugate of p_4 are added at the summation junction 108 to

generate first and second intermediate vectors, respectively. The angular part θ_1 of the first intermediate vector is computed at the CORDIC module 110 and the angular part θ_2 of the second intermediate vector is computed at the CORDIC module 112. The intermediate angles, θ_1 and θ_2, are then scaled by the timing weights M_1 and M_2,

5   respectively at the weighting modules 114 and 116 to generate 2 weighted angles. The weighted angles are then added at the summation junction 118 and then normalized by the ratio $1/(M_1+M_2)$ at the normalizing module 120 to generate a normalized angle. The normalized angle, which is the timing offset is then transferred to the timing loop filter 122 in order to complete the timing loop control operation, discussed hereinabove and

10   shown in more complete detail in Fig. 1. Note that although the CORDIC modules 110 and 112 are listed separately, they may physically represent a single time-shared hardware module.

The timing offset detection module 102 in Fig. 5 is operational during the data portion of the information packet, as specified in IEEE 802.11a-1999, and computes one

15   timing offset value per each data symbol in the packet. As was the case for the carrier offset detection discussed above, the timing weights M_1 and M_2 are calculated, at the modules 114 and 116 respectively, once during the preamble portion of the packet by the OWD module, immediately following the FEQ calculation and are based on the pilot tone FEQ coefficients, as discussed hereinbelow. The values M_1 and M_2 are then loaded into

20   timing offset detection module 102 and remain fixed for the subsequent decoding of the data portion of the packet.

Timing offset creates a phase effect across the OFDM pilot tones that varies linearly with frequency, or since the pilot tones are evenly spaced, the timing offset phase

varies linearly with pilot number. Accordingly, we can refer to the timing offset detection module 102 as the linear phase error (LPE^M) module in a manner consistent with the CPE^W module 71, wherein the superscript refers to the weights M_1 and M_2. For example, if the timing offset parameter to be measured is τ, then the resulting phase

5 effect on the four pilot tones would be $p_1 = e^{3\tau j}$, $p_2 = e^{\tau j}$, $p_3 = e^{-\tau j}$ and $p_4 = e^{-3\tau j}$, respectively. Given this particular timing offset, the output of the CORDIC module 110 would be

$$\theta_1 = \text{Angle}(p_2 + \text{conj}(p_3)) = \text{angle}(2\,e^{\tau j}) = \tau. \quad (3)$$

Similarly, the output of the CORDIC module 112 would be

10 $$\theta_2 = \text{Angle}(p_1 + \text{conj}(p_4)) = \text{angle}(2\,e^{3\tau j}) = 3\tau. \quad (4)$$

Note that the intermediate angle θ_1 is scaled by 3 prior to the weight module 114 and summation junction 118 to take into account the natural scaling between the pilot tone offset angles θ_1 and θ_2, as indicated by equations (3) and (4). A typical prior art receiver then might implement the LPE computation as:

15 $$\text{LPE} = (\theta_1 + \theta_2)/4.$$

In one embodiment of the present invention, in order to compute the weights M_1 and M_2, two intermediate weights, WI_1 and WI_2, are generated as

$$WI_1 = \text{round}(-\log(|FEQ_2|^2) - \log(|FEQ_3|^2)),$$

$$WI_2 = \text{round}(-\log(|FEQ_1|^2) - \log(|FEQ_4|^2)), \quad (5)$$

20 within the OWD module. In equation (5), $|FEQ_i|^2$ is the magnitude squared of the ith pilot tone FEQ coefficient, where $i = 1$ through 4. Then the timing weights that would be used in the timing offset detection module 102 are

$$M_1 = \text{round}(512 * WI_2 / (WI_1 + WI_2)),$$

and

$$M_2 = 512 - M_1. \qquad (6)$$

So that the LPE (linear phase error) becomes:

$$LPE^M = (M_1\theta_1 + M_2\theta_2) / 512. \qquad (7)$$

5   Equation (7) provides a weighting scheme between the two angles based on the relative

signal quality that exists between the two pairs of pilot tones (p_2, p_3) and (p_1, p_4), as

indicated by the cumulative channel fade conditions on the pilot subcarriers that is

contained in the corresponding FEQ coefficient magnitudes. The FEQ information is

used explicitly to compute the intermediate weights in equation (5). Equation (6) is used

10   to produce a pair of timing weights M_1 and M_2 that optimally combine the angle

measurements in a least squares error sense while maintaining the overall gain of the

timing offset module to be constant. Note that the added gain of $M_1 + M_2 = 512$ is

removed from the detector by the normalizing module 120 by implementing equation (7)

before the timing offset, i.e. LPE^M, is sent to the timing loop filter 122. Note, however,

15   that the number 512 was chosen to provide a reasonable amount of resolution between

the two weights. A smaller binary number, say 128 or 256, could also have been chosen

to implement and achieve similar performance. However the choice of a binary number

is desirable since it leads to hardware simplification by avoiding relatively expensive

multiplier operation due to the weights being implemented with shift operators.

20   To summarize, the timing offset detection module or the LPE^M module 102

computes an estimate of the instantaneous timing offset represented by LPE^M during the

steady state operation of the timing control loop, shown in Fig. 1. That is, the timing

offset is determined by computing the LPE^M. The LPE^M module 102 automatically

prevents the effects of multi-path channel fading from corrupting the LPE^M calculation by applying a set of weights to a pair of intermediate angles θ_1 and θ_2 that are computed using the pilot tones that are included with each data symbol in the information packet. The weights are computed once at the beginning of the packet during the preamble by the

5   OWD, and immediately after the computation of the FEQ. The pilot tone FEQ coefficients provide the channel fade information necessary to compute the set of weights, as specified by equations (5-6). The weights M_1, M_2, computed during the preamble, are transferred to the LPE^M module 102 to be used for steady state operation during the data portion of the information packet to provide active feedback control for

10   the timing control loop. As was true in the design of the CPE^W module 71, the LPE^M module 102 maintains constant gain as the timing weights are allowed to adapt to changing channel conditions. The LPE^M module 102 effectively mitigates the noise effects of the fading channel while maintaining the loop stability margins (gain and phase) that are necessary for reliable, robust performance in varying channel conditions.

15   It is noted that a conventional implementation of an OFDM modem receiver would not use the weighting schemes included in the LPE^M and CPE^W modules 102 and 71, respectively. For example, if the carrier and timing weights (W_1-W_4, M_1-M_2) were set to unity the carrier and timing offsets would rely solely on the averaging effects of all the pilot symbol additions. Alternatively, a conventional implementation of a least

20   squares (LS) algorithm might be used to compute the timing and carrier offsets jointly. However, by including the weights that are based on the FEQ magnitudes, the present invention uses a measure of the noise and channel-fading present in each of the pilot tones to improve the measurement of the offsets. Moreover, the weights computed using

equations (2) and (5-6) in common channel-fading conditions are proportional to the variances of the noise associated with the pilot tones (p_1, p_2, p_3, p_4) for the carrier offset, and the intermediate angles (θ_1, θ_2) in the timing offset. Hence, use of the aforementioned weights allows for a more optimal approximation to a weighted least

5   squares (WLS) estimate of the carrier and timing offsets.

Referring now to Fig. 6, a block diagram outlining computation of the timing weights M_1-M_2 and carrier weights W_1-W_4 is shown, in accordance with an embodiment of the present invention. Shown in Fig. 6 is a frequency domain equalizer training module (FTM) 200 coupled to offset weight determination (OWD) module 202, which is

10   coupled to timing offset detection module 204 and frequency or carrier offset detection module 206.

In the embodiment of the present invention shown in Fig. 1, the FTM 200 and OWD module 202 are located within the FEQ 26. However, in another embodiment of the present invention, the FTM and OWD module are located externally to the FEQ 26

15   but included within the modem receiver.

The preamble portion of the information packet received by the FTM 200 is used to train the FEQ, as discussed in the Provisional Patent Application referred to hereinabove. The FTM 200 generates pilot tone FEQ coefficients, which are transferred to the OWD module 202. The OWD module 202, using the pilot tone FEQ coefficients,

20   computes the carrier weights W_1-W_4 using equation (2) and the timing weights M_1 and M_2 using equation (6). The carrier and timing weights are computed using the preamble portion of the information packet. The carrier weights W_1-W_4 are transferred to the frequency offset detection module 206, while the timing weights M_1 and M_2 are

transferred to the timing offset detection module 204. The carrier and timing weights are subsequently used for steady state operation during the data portion of the information packet to mitigate the effects of multipath channel, as discussed hereinabove.

The modem receiver (shown in Fig. 1) includes a processor (not shown), or 5 computer medium, some type of storage area and a computer readable medium, for storing the software/firmware described in Figs. 4, 5, and 6. The processor executes codes from the computer readable medium for effectuating the functions outlined in Figs. 4, 5, and 6.

The present invention described hereinabove provides an efficient means and 10 apparatus for mitigating the effects of fading-channel conditions and allows the modem to reliably compensate for carrier frequency and timing offsets. In addition, the present invention allows maximum performance of the 802.11a/g receiver to be utilized and optimizes performance by mitigating the effects of multipath channel and/or inter-carrier interference (ICI). Accordingly, the present invention allows robust and high 15 performance reception of transmitted signals with minimal hardware cost.

Although the present invention has been described in terms of specific embodiment, it is anticipated that alterations and modifications thereof will no doubt become apparent to those more skilled in the art. It is therefore intended that the following claims be interpreted as covering all such alterations and modification as fall 20 within the true spirit and scope of the invention.

What is claimed is: